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Climate response to physiological forcing of carbon dioxide simulated by the coupled Community Atmosphere Model (CAM3.1) and Community Land Model (CLM3.0)

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[1] Increasing concentrations of atmospheric CO_2 decrease stomatal conductance of plants and thus suppress canopy transpiration. The climate response to this CO_2-physiological forcing is investigated using the Community Atmosphere Model version 3.1 coupled to Community Land Model version 3.0. In response to the physiological effect of doubling CO_2, simulations show a decrease in canopy transpiration of 8%, a mean warming of 0.1K over the land surface, and negligible changes in the hydrological cycle. These climate responses are much smaller than what were found in previous modeling studies. This is largely a result of unrealistic partitioning of evapotranspiration in our model control simulation with a greatly underestimated contribution from canopy transpiration and overestimated contributions from canopy and soil evaporation. This study highlights the importance of a realistic simulation of the hydrological cycle, especially the individual components of evapotranspiration, in reducing the uncertainty in our estimation of climatic response to CO_2-physiological forcing. **Citation:** Cao, L., G. Bala, K. Caldeira, R. Nemani, and G. Ban-Weiss (2009), Climate response to physiological forcing of carbon dioxide simulated by the coupled Community Atmosphere Model (CAM3.1) and Community Land Model (CLM3.0), *Geophys. Res. Lett.*, *36*, L10402, doi:10.1029/2009GL037724.

1. Introduction

[2] Increasing concentrations of carbon dioxide (CO_2) in the atmosphere have a direct effect on the physiology of plants: higher CO_2 tends to suppress plant transpiration through reduced stomatal conductance [*Collatz et al.*, 1992; *Field et al.*, 1995]. Because canopy transpiration is a major component of total evapotranspiration (ET) that consists of canopy transpiration, canopy evaporation, and soil evaporation, CO_2-induced changes in canopy transpiration will affect ET and latent heat flux to the atmosphere, thereby perturbing atmospheric energy balance and resulting in climate change. This CO_2-physiological forcing was observed to affect surface temperature and the hydrological cycle in both field experiments [*Hungate et al.*, 2002; *Long et al.*, 2006] and climate model simulations [e.g., *Sellers et al.*, 1996; *Betts et al.*, 1997; *Cox et al.*, 1999; *Gedney et al.*, 2006; *Betts et al.*, 2007; *Boucher et al.*, 2009]. These studies suggested that it is important to consider the physiological effects of CO_2, in addition to its greenhouse effect, in the projection of changes in climate and the hydrological cycle.

[3] Modeling studies have simulated land surface warming, reduced precipitation and increased runoff in association with reduced evapotranspiration caused by CO_2-physiological forcing. The simulated climatic effects vary among these studies for a doubling of CO_2. For instance, global mean land surface warming of 0.2 K from *Sellers et al.* [1996] and *Betts et al.* [1997], 0.4 K from *Cox et al.* [1999], and 0.5 K from *Boucher et al.* [2009] have been reported (Note: the CO_2-physiological effect reported by *Boucher et al.* [2009] was calculated in the transient simulations under the IS92a emission scenario, which have a CO_2 increase somewhat more than a doubling). The magnitude of changes shown by *Cox et al.* [1999] in hydrological parameters (e.g., precipitation, evaporation, and runoff) due to CO_2-physiological effect is larger (The CO_2-physiological effect on changes in global runoff, precipitation, and evaporation is 133%, −60%, and −350% of CO_2-radiative effect, respectively), but those shown by *Betts et al.* [2007] are smaller (59% of CO_2-radiative effect for mean runoff change and 6% for precipitation change). Recently, *Boucher et al.* [2009] simulated a physiological effect over land that is 40% of CO_2-radiative effect for mean runoff change, −20% for precipitation change and −150 % for surface evaporation change.

[4] In this study we examine the climatic effect of CO_2-physiological forcing using the Community Atmosphere Model version 3.1 (CAM3.1) [*Collins et al.*, 2004] coupled with Community Land Model version 3.0 (CLM3.0) [*Oleson et al.*, 2004]. CAM3.0 and CLM3.0 are the core atmosphere and land surface components of Community Climate System Model, CCSM3, [*Collins et al.*, 2006], a major climate model used in the Fourth Assessment Report (AR4) of the Intergovernmental Panel of Climate change [*Randall et al.*, 2007]. The aim of this study is to assess the CO_2-physiological effect in the CAM3.1/CLM3.0 model and compare our results with previous studies. Most previous modeling studies on the CO_2-physiological effect parameterize land surface processes based on the ‘‘MOSES’’ scheme [*Cox et al.*, 1999]. It is the first time that the CO_2-physiological effect is investigated using CLM as the underlying land surface model. By comparing our results

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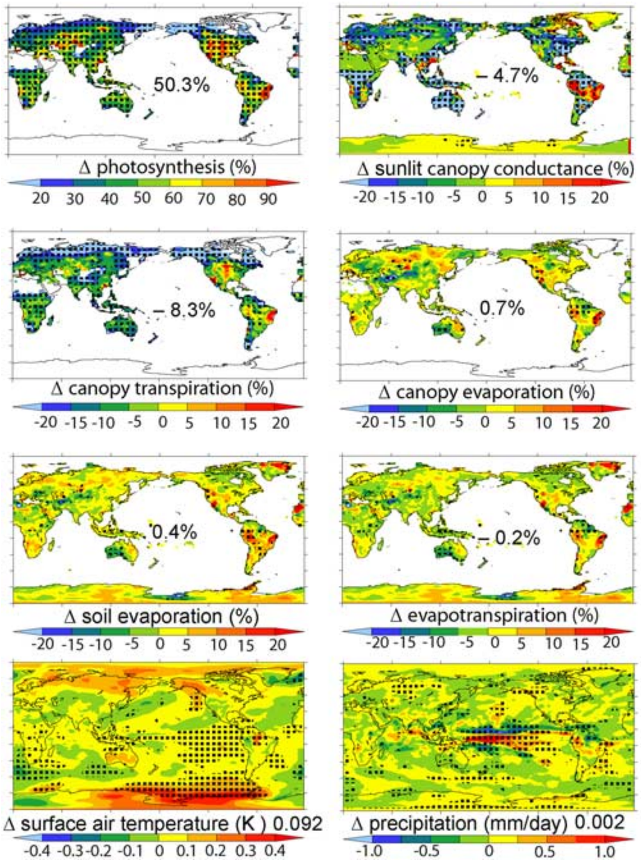

Figure 1. Effects of CO_2-physiological forcing in response to doubling CO_2 simulated by CAM3.1/CLM3.0. CO_2-physiological effects on temperature and precipitation are represented by the differences between the simulation of RAD_PHYS and RAD, while its effects on other variables are represented by the percentage difference between the simulation of RAD_PHYS and RAD [(RAD_PHYS − RAD)/RAD × 100%]. Dotted areas are regions where changes are statistically significant at the 5% level using Student *t*-test, and numbers are global mean results. Over most of the land surface, the changes in photosynthesis, canopy conductance, and canopy transpiration are statistically significant at the 5% level, but changes in canopy evaporation, soil evaporation, and total evapotranspiration are not statistically significant over most land surface. At the 5% level, changes in temperature and precipitation are statistically significant over only 7% and 11% of global land area, respectively.

with previously published ones, new insights would be gained for the key processes controlling climate response to CO_2-physiological forcing.

2. Method

2.1. Model

[5] The CAM3.1 model used here has 26 vertical levels and a horizontal resolution of 2.0° latitude by 2.5° longitude. It was run using the Finite Volume (FV) dynamical core and coupled to the CCSM slab-ocean/thermodynamic sea-ice model to allow for interactions between the atmosphere, ocean and sea ice. For the slab ocean simulations, the mixed layer depths were prescribed to climatological values. The prescribed ocean heat transport was derived from the net energy flux over the ocean surface in a simulation with prescribed sea surface temperature. The CLM3.0 model simulates a number of biophysical processes for different plant functional types (PFT) including stomatal physiology and photosynthesis, energy and momentum fluxes with vegetation canopy and soil, heat transfer in soil and snow, and hydrology of canopy, soil, and snow. In CLM3.0 changes in atmospheric CO_2 affect canopy photosynthesis and stomatal conductance, but do not alter the values of Leaf Area Index (LAI) and spatial distribution for each PFT, which are prescribed in the model. A detailed description of CLM3.0 is given by *Bonan et al.* [2002] and *Oleson et al.* [2004].

2.2. Simulation Setup

[6] CAM3.1/CLM3.0 was initially spun up for multi-decades to reach a quasi-steady state for present-day climate, and then three 50-year simulations were performed starting from this model spun-up: (1) a control simulation in which both atmospheric radiative transfer and plant physiology were forced by atmospheric CO_2 concentration of 355 ppm (CTR); (2) a simulation in which the radiative transfer model was forced by 2 × CO_2 concentration (710 ppm), but the calculations of plant physiology were carried out with 1 × CO_2 (355 ppm) (RAD); (3) a simulation in which both the calculations of radiative transfer and plant physiology were carried out with 2 × CO_2 (710 ppm) (RAD_PHYS). The last 20-year results for each simulation were used for analysis. The differences between the simulation of RAD and CTR give the effect of CO_2-radiative forcing, and the differences between the simulation of RAD_PHYS and RAD provide the effect of CO_2-physiological forcing.

3. Results

[7] The physiological effects of doubling CO_2 are shown in Figure 1 and Table 1; all results are annual-mean values averaged from the last 20-year simulations. In response to the physiological forcing of doubling CO_2, there is a general increase in photosynthesis and reduction in canopy conductance (Note: canopy conductance reported in this study is calculated from its maximum value in each month recorded in the monthly output file of CLM3.0, which provides an indication of the maximum ability for the plant to transpire during daytime). A decrease in sunlit canopy conductance occurs over most of the vegetated surface. In some areas, such as part of the Amazon, an increase in sunlit canopy conductance as a result of increased humidity is obtained. Globally averaged, there is about 50% increase and 5% decrease in photosynthesis and sunlit canopy conductance respectively, in response to a doubling of CO_2. Compared to sunlit canopy conductance, shaded canopy conductance is much smaller and its change is negligible (Table 1). As a result of the reduction in canopy conductance, canopy transpiration decreases in most vegetated areas with a global mean decrease of about 8%. Over most of the land surface, the changes in photosynthesis, canopy conductance and canopy transpiration are statistically significant at the 5% level. On the global scale, relative changes in canopy

Table 1. Global and annual mean changes in biophysical and climatic variables as a result of radiative and physiological effects of CO_2 doubling[a]

	CTR	RAD-CTR (Radiative Effect)	RAD_PHYS-CTR (Radiative + Physiological)	RAD_PHYS-RAD (Physiological Effect)
Photosynthesis (μmol m^{-2} s^{-1})	1.051	+0.008	+0.541	+0.533 (+50.30%)
Sunlit leaf stomatal conductance (mm s^{-1})	0.474	−0.008	−0.030	−0.022 (−4.72%)
Shaded leaf stomatal conductance (mm s^{-1})	0.090	−0.001	−0.001	0.0 (0%)
Canopy evaporation (mm day^{-1})	0.429	+0.005	+0.008	+0.003 (+0.70%)
Canopy transpiration (mm day^{-1})	0.146	+0.011	−0.002	−0.013 (−8.28%)
Soil evaporation (mm day^{-1})	1.383	+0.060	+0.066	+0.006 (+0.42%)
Total evapotranspiration (mm day^{-1})	1.957	+0.077	+0.072	−0.005 (−0.24%)
Global surface temperature (K)	287.366	+2.184	+2.276	+0.092 (+0.03%)
Land surface temperature (K)	284.817	+2.348	+2.470	+0.122 (+0.04%)
Ocean surface temperature (K)	289.154	+2.069	+2.139	+0.070 (+0.02%)
Global precipitation (mm day^{-1})	2.950	+0.125	+0.127	+0.002 (+0.07%)
Precipitation over land (mm day^{-1})	2.859	+0.141	+0.140	−0.001 (−0.03%)
Precipitation over ocean (mm day^{-1})	3.014	+0.114	+0.118	+0.004 (+0.13%)
Runoff over land (mm day^{-1})	0.422	+0.011	+0.011	0.0 (0%)
Precipitable water (kg/m2)	23.743	+3.476	+3.591	+0.115 (+0.42%)
Precipitable water over land (kg/m^2)	21.362	+3.207	+3.290	+0.083(+0.34%)
Global sensible heat flux (W m^{-2})	18.283	−1.123	−1.094	+0.029 (+0.17%)
Sensible heat flux over land (W m^{-2})	25.241	−0.516	−0.392	+0.154 (+0.62%)
Global latent heat flux (W m^{-2})	81.711	+3.496	+3.547	+0.051 (+0.06%)
Latent heat flux over land (W m^{-2})	56.810	+2.134	+1.973	−0.161 (−0.27%)
Net longwave radiation over globe (W m^{-2})	58.598	−3.340	−3.344	−0.004 (0.0%)
Net longwave radiation over land (W m^{-2})	63.175	−3.372	−3.306	+0.066 (+0.11%)
Net solar flux over global surface (W m^{-2})	159.656	−1.027	−0.956	+0.071 (+0.05%)
Net solar flux over land surface (W m^{-2})	147.223	−1.064	−0.840	+0.224 (+0.15%)
Total cloud cover (%)	0.588	+0.001	+0.001	0.0 (0%)
Total cloud cover over land (%)	0.567	+0.002	+0.002	0.0 (0%)

[a] CO_2-radiative effects are represented by the difference between RAD and CTR simulations; CO_2-physiological effects are represented by the difference between RAD_PHYS and RAD simulations; and the combined CO_2-radiative and CO_2-physiological effects are represented by the differences between the RAD_PHYS and CTR simulations. Percentage numbers are the percentage changes between the simulation of RAD_PHYS and RAD calculated as (RAD_PHYS - RAD)/RAD $\times$ 100%.

evaporation (0.7% increase) and soil evaporation (0.4% increase) caused by CO_2-physiological forcing are much smaller than that of canopy transpiration (8% decrease). However, there is only a 0.2% decrease in global evapotranspiration (ET) despite the 8% decrease in canopy transpiration. The small change of ET in response to CO_2-physiological forcing is mainly a result of the low contribution of canopy transpiration to ET in the control simulation (Figure 2); canopy transpiration accounts for only about 7% of the global ET, while canopy and soil evaporation, respectively, accounts for 22% and 71% of the global ET. This is in sharp contrast to the ensemble results from a broad range of land surface models in which global evapotranspiration is dominated by transpiration (48%), with substantially smaller contributions from canopy evaporation (16%) and soil evaporation (36%) [*Dirmeyer et al.*, 2006].

[8] In response to the physiological forcing of doubling CO_2, the model simulates a warming over much of the land surface with pronounced warming seen in parts of the high latitudes of the Northern and Southern Hemisphere, and a small region of the Amazon. Cooling is observed in large parts of the Eurasia and parts of the North and South America. Most temperature change over land is not statistically significant at the 5% level, except for a few areas such as a small section of the Amazon and small patchy areas of Africa (Figure 1). Averaged over the global land surface, the model simulates a warming of about 0.1 K (Table 1), which is lower than previous results of 0.2 K from *Sellers et al.* [1996] and *Betts et al.* [1997], 0.4 K from *Cox et al.* [1999], and 0.5 K from *Boucher et al.* [2009]. In terms of the hydrological cycle, the model simulates a 0.001 mm day^{-1} (0.03%) reduction in precipitation over land and a negligible change in river runoff as a result of CO_2-physiological forcing. For comparison, in response to the physiological effect of doubling CO_2, *Cox et al.* [1999] simulated a 0.03 and 0.04 mm day^{-1} reduction in precipitation and runoff; *Betts et al.* [2007] reported a 0.14 (7%) and 0.06 (6%) mm day^{-1} reduction in precipitation and runoff. Relative to the CO_2-radiative effect, our simulated climatic effects of CO_2-physiological forcing are negligible (Table 1; 0% of CO_2-radiative effect for runoff changes, 0.7% for precipitation changes, and 6% for evapotranspiration changes), which is in sharp contrast to other modeling studies [*Cox et al.*, 1999, *Betts et al.*, 2007, *Boucher et al.*, 2009] that report comparable or larger hydrological changes from CO_2-physiological effect.

4. Discussion and Conclusions

[9] Enhanced CO_2 concentrations reduce canopy transpiration by their physiological effects on stomatal conductance. The decreased canopy transpiration leads to reduced latent heat flux to the atmosphere, which tends to warm the land surface. In the simulation presented here using CAM3.1/CLM3.0 model, canopy transpiration decreases by about 8% in response to the physiological effect of doubling CO_2. However, there is only a 0.16 W m^{-2} reduction in the latent heat flux from the land to the atmosphere, corresponding to a reduction in total evapotranspiration of 0.005 mm day^{-1}. For comparison, *Boucher et al.* [2009] and *Cox et al.* [1999] found a 0.05 and 0.07 mm day^{-1} reduction in total evapotranspiration respectively,

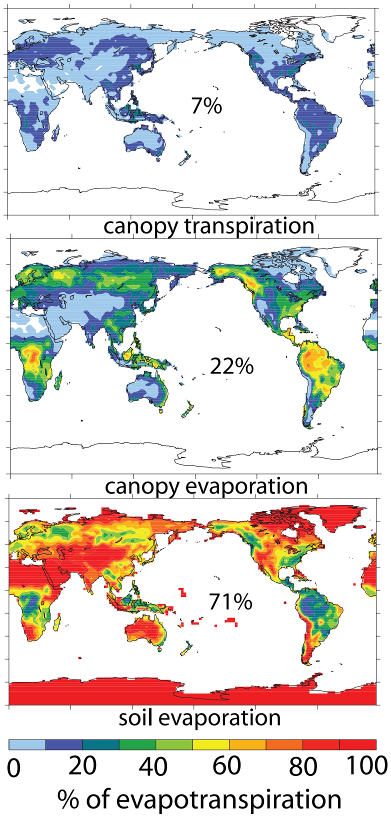

Figure 2. Percentage contributions of canopy transpiration, canopy evaporation, and soil evaporation to total evapotranspiration in the control simulation of CAM3.1/CLM3.0. Numbers are global mean values. Compared with the ensemble results from a broad range of land surface models (48% of global evapotranspiration is from transpiration, 16% is from canopy evaporation, and 36% is from soil evaporation) [*Dirmeyer et al.*, 2006], the model greatly underestimates the contribution from canopy transpiration (7%) to total evapotranspiration and overestimates the contributions from canopy (22%) and soil (71%) evaporation.

which is an order of magnitude larger than our results. The small reduction in latent heat flux and evapotranspiration simulated here is mainly attributed to the unrealistic partitioning of evapotranspiration in the control simulation, in which evapotranspiration is dominated by evaporation from soil and canopy, while the contribution from canopy transpiration is only 7%. Thus, CO_2-induced reduction in canopy transpiration has little effect on total evapotranspiration.

[10] As a result of the insignificant response in evapotranspiration, the climate effect of CO_2-physiological forcing in the CAM3.1/CLM3.0 simulation is much smaller than previous studies [e.g., *Sellers et al.*, 1996; *Betts et al.*, 1997; *Cox et al.*, 1999; *Betts et al.*, 2007; *Boucher et al.*, 2009]. Differences in climate feedbacks and ocean-atmosphere interactions between models might contribute somewhat to differences in modeled climatic response to CO_2-physiological forcing. For example, fixed sea surface temperature was used in *Sellers et al.* [1996] and *Cox et al.* [1999]; *Betts et al.* [1997, 2007], together with this study, coupled the land and atmosphere components to a slab ocean model; *Boucher et al.* [2009] used a coupled ocean-atmosphere model. But the insensitivity of climate response to CO_2-physiological forcing simulated here can be mainly attributed to the unrealistic partitioning of evapotranspiration in the control simulation. The bias in evapotranspiration partitioning of CLM3.0 was also observed in a number of studies [e.g., *Dickinson et al.*, 2006; *Lawrence et al.*, 2007; *Lawrence and Chase*, 2007] and was found to be a result of several deficiencies in its canopy and soil parameterizations related to the hydrological cycle. Significant improvement in the partitioning of evapotranspiration was achieved in the most recently released version of community land model (CLM3.5) through the implementation of new datasets and improved parameterizations for canopy integration, canopy interception, soil evaporation, and soil water availability [*Oleson et al.*, 2008]. The more realistic partitioning of evapotranspiration is expected to increase the model's sensitivity to CO_2-physiological forcing.

[11] In summary, this study demonstrates the importance of a realistic simulation in the surface hydrological cycle, especially the individual components of evapotranspiration, for the assessment of CO_2-physiological effects. More studies are needed to reduce the uncertainty in our estimation of climatic response to CO_2-physiological forcing, which is important for the projection of future climate, especially for the flood and drought risks associated with changes in the hydrological cycle [*Betts et al.*, 2007].

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